Photofunctionalized Dental Implants: A Case Series in Compromised Bone

Akiyoshi Funato, DDS[1]/Takahiro Ogawa, DDS, PhD[2]

Purpose: Ultraviolet (UV) light treatment of titanium, or photofunctionalization, has been shown to enhance its osteoconductivity in animal and in vitro studies, but its clinical performance has yet to be reported. This clinical case series sought to examine the effect of photofunctionalization on implant success, healing time, osseointegration speed, and peri-implant marginal bone level changes at 1 year after restoration. ***Materials and Methods:*** Four partially edentulous patients were included in the study. Seven implants with identical microroughened surfaces were photofunctionalized with UV light for 15 minutes. Osseointegration speed was calculated by measuring the increase in implant stability quotient (ISQ) per month. Marginal bone levels were evaluated radiographically at crown placement and at 1 year. ***Results:*** All implants placed into fresh extraction sockets, vertically augmented bone, simultaneously augmented sinuses, or the site of a failing implant remained functional and healthy at 1 year, even with an earlier loading protocol (2.1 to 4.5 months). ISQs of 48 to 75 at implant placement had increased to 68 to 81 at loading. In particular, implants with low primary stability (initial ISQ < 70) showed large increases in ISQ. The speed of osseointegration of photofunctionalized implants was considerably greater than that of as-received implants documented in the literature. Mean marginal bone levels were –0.35 ± 0.71 mm at crown placement and had significantly increased to 0.16 ± 0.53 mm at 1 year, with coronal gains in marginal bone level that surpassed the implant platform. No implants showed marginal bone loss. ***Conclusions:*** Within the limits of this study, photofunctionalization expedited and enhanced osseointegration of commercial dental implants in various clinically challenging/compromised bone conditions. Photofunctionalization resulted in preservation—and often a gain—of marginal bone level, and long-term large-scale clinical validation is warranted. Int J Oral Maxillofac Implants 2013;28:1589–1601. doi: 10.11607/jomi.3232

Key words: *hydrocarbon, photofunctionalization, superhydrophilicity, titanium implants, ultraviolet*

In spite of many successful developments and improvements in implant dentistry, clinical challenges remain. It would be an advantage to reduce the healing time required for osseointegration to reduce patient morbidity and accommodate the growing demands of modern implant therapy. Several risk factors, such as poor bone quality and quantity, diabetes, osteoporosis, and smoking, may limit its application and decrease success rates.[1–4] Preimplantation surgery, such as bone augmentation and sinus elevation, has been introduced to expand the indications for implant therapy. However, the additional surgical intervention increases patient morbidity, and prognosis in these complex cases is not as predictable.[5,6] Protocols designed to expedite treatment, such as implant placement into fresh extraction sockets and immediate loading, may also compromise outcomes.[7,8] Further improvements in the ability and capacity of dental implants to osseointegrate are therefore required.

It is well known that implants fail because of unsuccessful, or destructive changes in, osseointegration.[9–11] However, it remains uncertain why bone tissue does not completely form around implant surfaces, even under normal biologic conditions. The average total implant area eventually covered by bone (bone-implant contact [BIC]) is reported to be only 45% ± 16%,[12] or between 50% and 75%,[13–15] which is far lower than the ideal 100%.

[1]Private Practice, Nagisa Dental Clinic, Kanazawa, Japan.
[2]Professor, Laboratory for Bone and Implant Sciences, The Weintraub Center for Reconstructive Biotechnology, Division of Advanced Prosthodontics, UCLA School of Dentistry, Los Angeles, California, USA.

Correspondence to: Dr Takahiro Ogawa, Laboratory for Bone and Implant Sciences, The Jane and Jerry Weintraub Center for Reconstructive Biotechnology, Division of Advanced Prosthodontics, Biomaterials and Hospital Dentistry, UCLA School of Dentistry, 10833 Le Conte Avenue (B3-081 CHS), Box 951668, Los Angeles, CA 90095-1668. Fax: +310-825-6345. Email: togawa@dentistry.ucla.edu

Ultraviolet (UV) light–mediated photofunctionalization of titanium has recently attracted considerable attention as a means to improve the osteoconductivity of titanium implants.[16–18] UV treatment of titanium surfaces has been shown to increase their bioactivity and osteoconductivity because it restores their superhydrophilicity, reducing surface carbon and optimizing surface electrostatic charges.[19–21] These biologic and physicochemical features are collectively known as *photofunctionalization*.[16,18,22,23] Photofunctionalized surfaces show increased protein adsorption and increased migration, attachment, and proliferation of osteogenic cells (two- to fivefold) in vitro.[20,24,25] The biomechanical strength of photofunctionalized implants is threefold higher than that of untreated implants at the early healing stage in animal modeling in vivo.[24] This enhanced osseointegration persists, even in late healing stages, and is associated with 98.2% BIC around photofunctionalized implants, compared to less than 55% around untreated controls.[24]

This enhanced level of peri-implant bone morphogenesis has been termed "superosseointegration," where "super" represents the maximum degree of, and minimum resistance to, the phenomenon.[22,23,26–28] In addition to near-maximal BIC, osteomorphogenesis around photofunctionalized implants is characterized by significantly reduced amounts of soft tissue between the implant and bone. Soft tissue growth between an implant and bone is a barrier to osseointegration but is reduced to less than 1% around photofunctionalized implants, compared to more than 20% around untreated implants.[24] The potential advantages of photofunctionalized implants in unfavorable bone milieu have also been demonstrated in animal models. Enhanced osseointegration by photofunctionalization overcomes the reduced loading capacity of short implants and a lack of cortical bone support.[17,29] Photofunctionalization is therefore proven not only to expedite osseointegration but also to increase overall levels of osseointegration, which may potentially overcome the drawbacks of compromised healing environments.

The long-term stability of the peri-implant tissues is of critical clinical importance, but no complete solution has yet been put forth.[30–34] In particular, maintenance of marginal bone levels (MBLs) around implants has been a challenge.[30] It is accepted that unavoidable marginal bone loss occurs, which may cause esthetic problems and eventually lead to unfavorable mid- and long-term prognoses of implants.[8,35–40] Marginal bone loss of 1 mm or more can be expected during the initial stages after placement, depending on the geometric features of the surrounding bone and healing conditions.[35–37,39,41–43] Furthermore, progressive reduction of 0.2 mm per year, after the first year, is reluctantly considered to be a clinical success.[40] The authors hypothesize that the enhanced osteoconductive capability of photofunctionalized implants may not only improve osseointegration around the main body and apical part of an implant but also osteomorphogenesis around the implant neck, which would be expected to result in an improved bone seal and bone maintenance toward the coronal zone.

Photofunctionalization is different from other surface modification techniques because of its simple and unique delivery method and versatility. Photofunctionalization is neither an additive nor a subtractive method of surface modification. Titanium implant surfaces, regardless of experimental or commercial use, are chemically contaminated with unavoidable and progressive deposition of hydrocarbons.[24,25,44–54] Photofunctionalization cleanses these surfaces by removing these hydrocarbons through titanium dioxide (TiO_2)–mediated photocatalysis and direct decomposition by UV light.[20,55] As a result of this chemical cleaning, the superhydrophilicity that is lost on sufficiently aged titanium surfaces can be regained.[21,56] Photofunctionalization is effective on various types of titanium surfaces, including so-called smooth (eg, machined) and microroughened (eg, acid-etched and sandblasted) surfaces, without altering their existing topography, roughness, or other morphologic features.[24,29]

It remains unknown whether photofunctionalization is effective in clinical use. Therefore, to obtain preliminary data regarding the effects of photofunctionalization, the authors undertook a clinical case series of photofunctionalized dental implants placed in compromised bone. The present paper discusses whether the clinical outcomes of photofunctionalized implants at 1 year of follow-up are comparable to the efficacy observed in animal and in vitro studies.

MATERIALS AND METHODS

Patient Selection

Four patients (two men and two women) aged 38 to 72 years (average, 52 years) visited Nagisa Dental Clinic during August and November 2010 for implant therapy and provided consent for documentation and public presentation of their cases. These patients met the following criteria: They were at least 20 years old; they complied with oral health care instructions and attended necessary visits; and all had indications for implant placement in clinically difficult conditions of a fresh extraction socket, staged or simultaneous vertical or lateral bone augmentation, sinus-augmented site, replacement of failing implants, or a combination of these. Patients with systemic or behavioral conditions that could potentially affect bone and soft

Fig 1a The photo device used for photofunctionalization of dental implants (TheraBeam Affiny). Implants are placed on a sliding stage. The device performs an automatic program of 15 minutes of UV exposure and 5 minutes of ventilation.

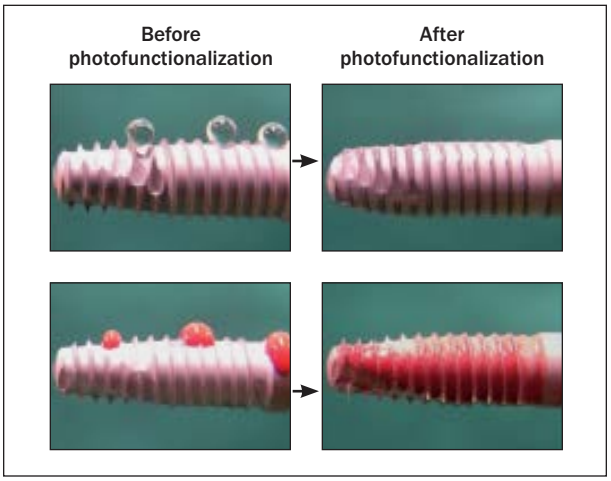


Fig 1b Superhydrophilic and superhemophilic surfaces of dental implants after photofunctionalization. Images show droplets of 3 µL of double-distilled water and rat blood placed on implant surfaces (*left*) before and (*right*) after photofunctionalization. After photofunctionalization, 9 µL of double-distilled water or blood (three droplets of 3 µL each) was sufficient to spread and cover the entire surface of a dental implant.

tissue healing, such as osteoporosis, diabetes, radiation treatment, bruxism, or smoking, were excluded from the study.

Clinical Procedures and Photofunctionalization of Dental Implants

Standardized consultation and diagnostic procedures were provided to all patients, and a treatment plan was presented to and approved by each patient. Following administration of routine local anesthesia and reflection of a full-thickness flap, implants were placed with a torque of 25 to 45 Ncm following the standard surgical procedure recommended by the manufacturer. The implants used in this study had a tapered root-form geometry and were of identical surface topography (Osseotite Certain, Biomet/3i). All implants were photofunctionalized through treatment with UV light for 15 minutes with a photo device (TheraBeam Affiny, Ushio); this was done chairside immediately before placement (Fig 1a). The photofunctionalization-induced change in surface property, from hydrophobic to superhydrophilic, was confirmed prior to the procedure by examining several implants for their wettability to double-distilled water and blood (Fig 1b). The tested implants were from a separate group of the same type of implants and were not used in patients after hydrophilicity testing. The flap was closed by a submerged or nonsubmerged technique.

Patients returned to the clinic at approximately halfway through the healing time based on a routine protocol established in the clinic for each specific complex case. Implants were functionally loaded with provisional restorations if the patient was free from discomfort or pain and there was no (*1*) immature healing or inflammation in the peri-implant tissues, (*2*) peri-implant radiolucency, or (*3*) implant mobility. Loading was performed if implant stability quotients (ISQs) were 65 or higher. ISQs between 60 and 65 are considered sufficiently healed for successful loading or definitive restoration,[57–61] and implants with an ISQ of 65 and higher have been shown to successfully withstand immediate and early loading; this is therefore often used as a criterion in these protocols.[62–65]

Assessment of Osseointegration

Successful osseointegration was determined clinically and radiographically according to the criteria established by Smith and Zarb.[40] Osseointegration speed was evaluated by measuring the increase in ISQ per month using the Osstell ISQ implant stability device (Osstell). The ISQ increase per month was defined as ([ISQ at the commencement of loading] – [ISQ at implant placement])/(healing time required before loading).

Implant Success

Implant success was determined according to the criteria of Smith and Zarb.[40] If an implant showed significant mobility, radiographically determined failure of osseointegration or progressive disintegration, significant marginal bone loss, pain, inflammatory signs, or rapid and continuous decreases in ISQ, it was considered a failure.

Table 1 Case Description and Clinical Outcome Parameters

			ISQ			MBL		
Patient	Surgical procedure	Time before loading (mo)	At implant placement	At loading	Increase per month	At definitive restoration	After 1 y	Change
Patient 1	Immediate replacement of failing implant	2.1				–0.8 (M) –1.4 (D)	–0.2 –0.7	+0.6 +0.7
Patient 2	Simultaneous sinus elevation	3.8	48	76	7.36	0.4 (M) 1.0 (D)	0.4 1.0	0.0 0.0
			49	80	8.16	1.0 (M) –0.6 (D)	1.0 –0.4	0.0 +0.2
Patient 3	Fresh extraction socket	2.1	67	72	2.38	–0.3 (M) –1.1 (D)	0.5 –0.6	+0.8 +0.5
Patient 4	Staged approach: Vertical GBR and sinus elevation	4.5	67	80	2.89	–0.8 (M) –0.7 (D)	–0.2 0.0	+0.6 +0.7
			75	81	1.33	–0.2 (M) –0.6 (D)	0.5 0.2	+0.7 +0.8
			73	68	–1.11	–0.7 (M) –0.2 (D)	0.5 0.2	+1.2 +0.4
Mean		3.6	63.2	76.2	3.5	–0.35	0.16	0.51
SD		1.0	11.8	5.2	3.5	0.71	0.53	0.35

GBR = guided bone regeneration; M = mesial; D = distal.

Marginal Bone Change

Marginal bone change was evaluated by measuring the potential difference in peri-implant MBL occurring at 1 year after placement of the definitive prostheses. Periapical radiographs were taken at the time of definitive prosthesis placement and 1 year later. A hard plastic occlusal jig was used to standardize the film angulation. When required, the measured dimensions were calibrated on the basis of the known implant length. The most coronal point of BIC was identified, and the difference between the implant platform and the contact end was considered as the MBL. The values were negative when the first bone contact was located apical to the implant platform, whereas they were positive when the first bone contact was located coronal to the implant platform. Measurements were performed on both the mesial and distal sides of an implant. If the MBL decreased at the 1-year visit, the value was considered a negative change.

Assessment of Surgical and Prosthetic Complications

Potential surgical complications, including duration and level of pain, bleeding, inflammatory reactions of tissues, inadequate primary stability of implants, improper or delayed wound healing, and postoperative infection, were monitored with regard to the use of photofunctionalized implants. The authors determined whether these complications were significantly different from those observed with conventional protocols without the use of photofunctionalization.

With respect to the use of photofunctionalized implants, potential prosthetic complications were monitored, including the necessity for extra procedures or significant procedural modifications or any difficulty experienced during abutment connection, provisionalization, definitive restoration, and follow-up visits.

Statistical Analysis

MBLs were measured on both the mesial and distal sides of an implant (n = 14). A paired *t* test was used to examine the difference between the time of crown placement and 1 year after crown placement; $P < .05$ was considered statistically significant.

RESULTS

Clinical data on the treated patients are summarized in Table 1.

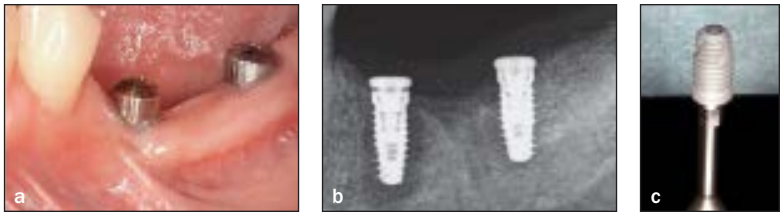
Case Presentations

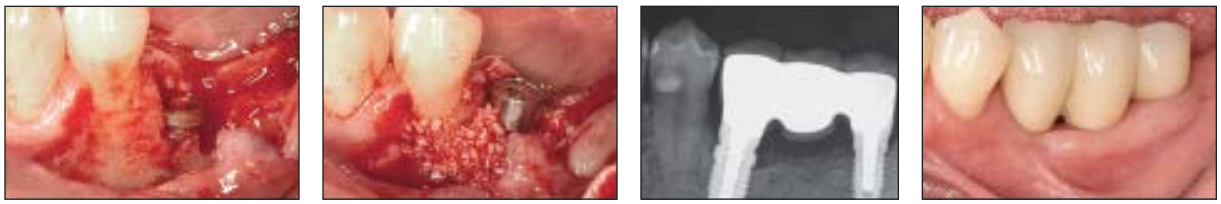
Patient 1: Immediate replacement of a failing implant with simultaneous guided bone regeneration. A 38-year-old man was referred to the clinic because of an implant that was failing as a result of placement into suspected overheated bone at the site of the mandibular left second premolar (Figs 2a and 2b). Immediately after removal of the failed implant (4 mm in diameter, 10 mm in length) and curettage, a photofunctionalized implant (5 mm in diameter, 10 mm in length) was

Figs 2a to 2h *Patient 1. Immediate replacement of a failing implant performed with simultaneous guided bone generation.*

Figs 2a and 2b Intraoral and periapical radiographic images of a failing implant placed at the site of the lower left second premolar.

Fig 2c A photofunctionalized implant placed after removal of the failing implant. The photofunctionalized implant surface was highly hemophilic.





Figs 2d and 2e A significant horizontal and vertical gap was present between the new implant and the alveolus and was filled with bone graft material.

Figs 2f and 2g Radiographic and intraoral images with the definitive prosthesis in place.

placed into the site (Fig 2c). The highly hemophilic surface of the photofunctionalized implant was confirmed during placement. The failed and new implants had identical surface topography and had been obtained from the same manufacturer. There was little supporting bone; the gap between the implant and the existing alveolar ridge was 3.5 mm (Fig 2d). This gap was filled with bone substitute materials (Bio-Oss Cancellous 0.25- to 1.00-mm particles, Geistlich) (Fig 2e) and closed using a submerged technique with a titanium membrane (Frios Boneshield, Dentsply Friadent) without fixation.

After 2.1 months of healing, radiographs showed that mature bone surrounded the replaced implant. The membrane was removed, and stage-two surgery was carried out. The implant, along with an existing one at the first molar site, was provisionalized at this time and functional loading was initiated. Four months after implant placement (1.9 months after functional provisionalization), the definitive prosthesis was placed (Figs 2f and 2g). There were no surgical or prosthetic complications during the treatment and follow-up visits up to 1 year. Periapical radiographs at the time of crown placement and the 1-year follow-up visit were compared to evaluate potential changes in MBLs (Fig 2h). The radiolucency around the implant neck that was present at the time of crown placement disappeared or was less apparent at the 1-year follow-up visit at both the mesial and distal aspects of the implants. Accordingly, the BIC moved closer to the platform level (arrows in Fig 2h).

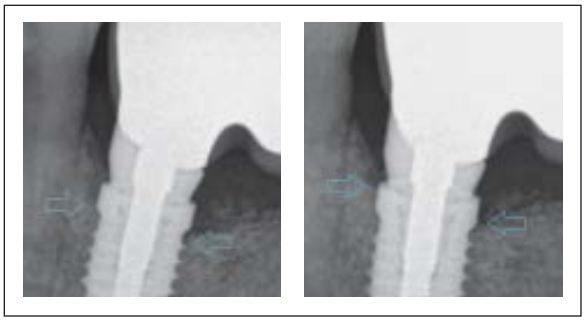
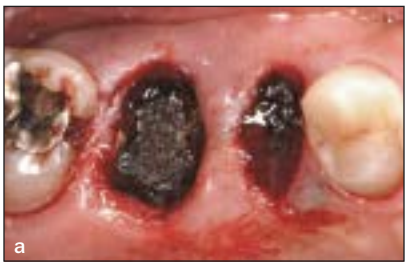
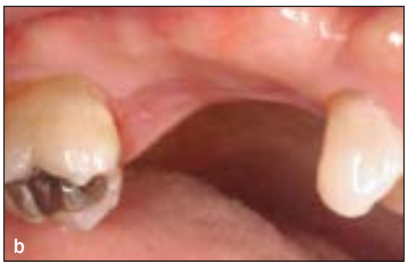


Fig 2h A radiographic comparison of marginal bone level at (*left*) the time of crown placement and (*right*) at the 1-year follow-up visit. Blue arrows indicate the first BIC.

Patient 2: Implant placement with simultaneous sinus elevation. A 45-year-old man visited the clinic for restoration of the maxillary right second premolar and first molar with a particular consideration for dental implants. These teeth had been extracted because of severe caries and infected root canals (Fig 3a). Two months after extraction (Fig 3b), two photofunctionalized implants were placed into the sites, with the posterior one requiring simultaneous sinus elevation (Fig 3c). The implant in the second premolar site was 4 mm in diameter and 13 mm in length, whereas the implant at the first molar site was 5 mm in diameter and 13 mm in length. Support from the native bone for the first molar implant was limited, with only the coronal 6 mm of the implant being in contact with the native bone; the remaining structure (the apical 7 mm) was in the elevated sinus (Fig 3d). Clinically, the quality of the native bone was poor (spongy and soft), as evidenced by low ISQs (< 50; see Table 1). The sinus was elevated using the lateral window technique and bone substitute was used to fill the cavity (Bio-Oss Cancellous 0.25- to 1.0-mm particles). The implant in the second premolar site was placed entirely within native bone (Fig 3e). Both implants underwent submerged healing.

Figs 3a to 3f *Patient 2: Implant placement with simultaneous sinus elevation.*





Figs 3a and 3b Intraoral images (*a*) immediately and (*b*) 2 months after extraction of the maxillary right second premolar and first molar.

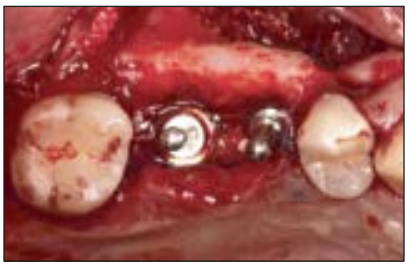
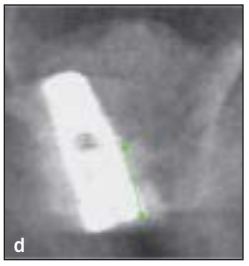
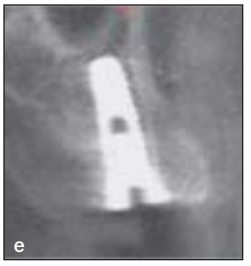


Fig 3c Two months after the extractions, implants were placed with simultaneous sinus elevation in the first molar region.





Figs 3d and 3e Computed tomographic images of the (*d*) first molar and (*e*) second premolar implants. Note that the implant at the site of the first molar is supported by native bone only for the coronal 6 mm (*green line*).

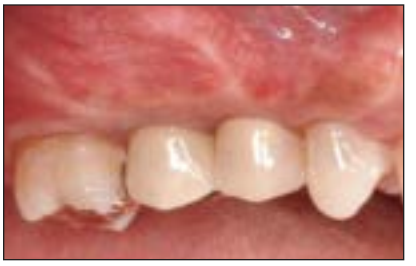


Fig 3f Definitive restorations in place.

After 3.8 months of healing, a second surgery was performed, and the implants were loaded on the same day. The definitive restoration was placed 1.2 months after provisionalization (Fig 3f). In this patient, changes in implant stability were evaluated by measuring the ISQs at implant placement and at loading. At implant placement, the ISQs were 48 and 49 for the second premolar and first molar sites, respectively; 3.8 months later, at loading, these had increased to 76 and 80. The osseointegration speed, defined as the increase in ISQ per month, was 7.36 and 8.16 for the second premolar and first molar sites, respectively.

Patient 3: Implant placement into a fresh extraction socket. A 53-year-old woman presenting with a distal periodontal lesion and bone resorption around the maxillary left first premolar visited the clinic for potential implant treatment. Clinical and radiographic examination indicated that the lesion was caused by a distal crack of the tooth (Fig 4a). The first premolar was extracted, and a photofunctionalized implant (4 mm in diameter and 13 mm in length) was placed immediately (Fig 4b). Although little cortical support was available, as shown by a 2.5-mm gap between the implant and the buccal alveolar ridge (Fig 4c), the apical half of the implant was within the native bone, with good primary stability (ISQ > 65). Blood clot was maintained in the gap by means of carbon dioxide laser–mediated hemostasis and the wound was closed using a non-submerged technique without any grafting materials (Fig 4d). The patient received antibiotic treatment for 3 days postsurgery.

At 2.1 months after placement, the implant was functionally provisionalized and also utilized as an orthodontic anchor to extrude the second premolar (Fig 4e). The definitive restoration was placed 6 months after initial implant placement, ie, 3.9 months after provisionalization (Fig 4f). The extrusion was performed for 3 months with 0.16-inch nickel-titanium wire, with generation of a constant force of approximately 50 g anticipated. Extrusion of the neighboring tooth, in combination with the use of the photofunctionalized implant, effectively increased the MBL. A significant gain in the MBL at both the mesial and the distal aspects of the implant was clearly demonstrated by radiographs before and after tooth extrusion (blue arrows in Fig 4g). Moreover, the maturation of bone stretching from the middle third of the implant to the existing peri-implant marginal gap was uniquely observed as developing intensity and continuity of mineralization along the interface (yellow arrows in Fig 4g). Accordingly, formation of the mesial and distal interproximal papillae was achieved, as seen in the definitive restoration (Fig 4f). This implant was also evaluated for stability during healing. At implant placement, the ISQ was 67, whereas at the time of provisionalization it was 72, indicating an average ISQ increase of 2.38 per month.

Fig 4a to 4g *Patient 3: Implant placement into a fresh extraction socket.*

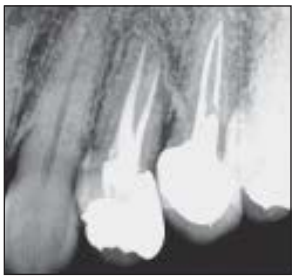
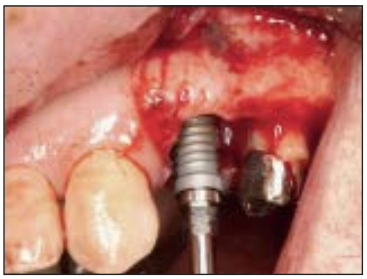
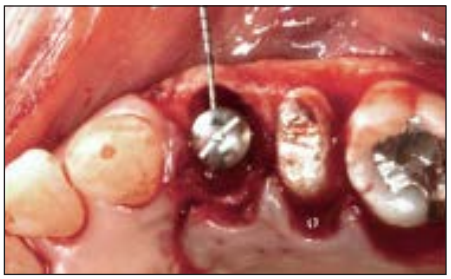


Fig 4a Radiograph of a maxillary left first premolar presenting a distal bone resorption associated with a crack.





Figs 4b and 4c Intraoral images obtained during implant placement. The implant surface was highly hemophilic after photofunctionalization. The light-colored blood plasma could be seen climbing up the implant surface along the thread as soon as the implant makes contact with blood. Blood plasma reaches the coronal end first, with the denser, red, erythrocyte-containing blood constituents following. There was no crestal bone support and a significant horizontal gap of 2.5 mm between the buccal alveolus and the implant surface.

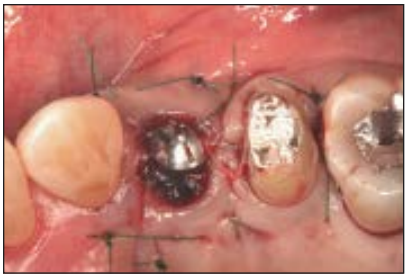


Fig 4d The implant site was sutured without grafting materials using a nonsubmerged technique. Blood clot was formed and retained in the peri-implant gap by using carbon dioxide laser–mediated hemostasis.

Fig 4e After 2.1 months of healing, the implant was provisionalized and used as an orthodontic anchor to extrude the second premolar.

Fig 4f Definitive restoration.

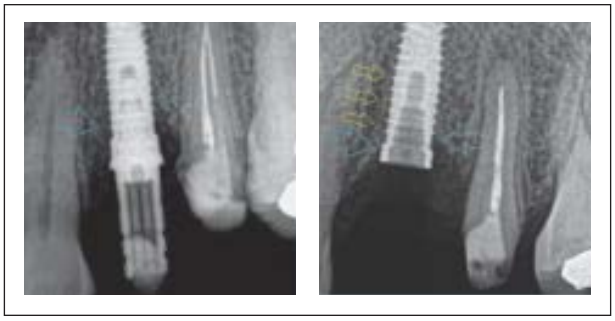


Fig 4g Radiographic comparison (*left*) before and (*right*) after the orthodontic procedure. Bone maturation is seen along the implant interface (*yellow arrows*). New bone formation is in progress within the peri-implant gap at both the mesial and the distal sides, significantly increasing the marginal bone level. Blue arrows indicate the most coronal BIC.

Patient 4: Staged placement after vertical ridge augmentation and sinus elevation. A 72-year-old woman visited the clinic for implant restoration in the maxillary left quadrant. The alveolar ridge in the area was highly resorbed, as seen in the radiographs (Fig 5a). A combination of vertical ridge augmentation and sinus elevation was performed in this area to obtain a sufficient quantity of bone for implant placement (Figs 5b to 5d). After 6.5 months of healing, three photofunctionalized implants were placed for nonsubmerged healing (second premolar, 4 × 13 mm; first molar, 5 × 13 mm; second molar, 6 × 10 mm) (Fig 5e). As seen radiographically before site development (Fig 5a), there was limited native bone support of only 25% to 30% for the two posterior implants. After 4.5 months, the implants were provisionalized for functional loading, followed by definitive restoration at 6 months after implant placement (Figs 5f and 5g). Radiographic comparison of images taken at the time of crown placement and 1 year later showed relocation of marginal bone contact toward the coronal ends of the implants in many areas (arrows in Fig 5h).

Implant Success

The healing time before functional provisionalization ranged from 2.1 to 4.5 months in these difficult cases.

Figs 5a to 5h *Patient 4: Staged implant placement after vertical ridge augmentation and sinus augmentation.*

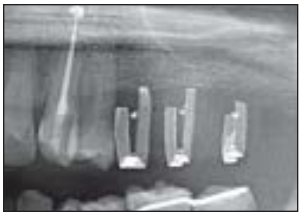
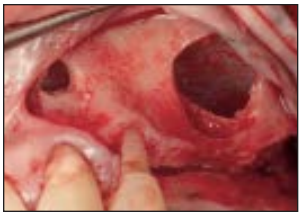


Fig 5a A panoramic radiograph was obtained with a surgical stent before site development surgery.



Figs 5b and 5c Intraoral images before and during a combination of sinus elevation and vertical ridge augmentation.

Fig 5d Radiograph confirms placement of the sinus graft.

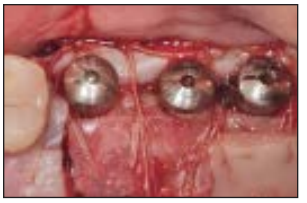
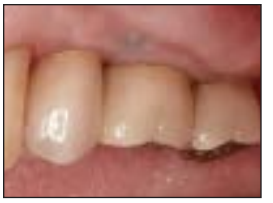


Fig 5e Three implants were placed 6.5 months after site development.



Figs 5f and 5g Intraoral view and periapical radiograph with definitive restorations in place.

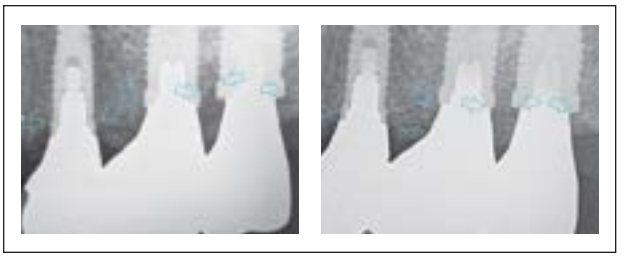


Fig 5h Radiographic comparison highlighting marginal bone levels (*left*) at the time of crown placement and (*right*) at 1 year. Blue arrows indicate the first BIC.

During the 1-year follow-up period after placement of the definitive prostheses, all seven photofunctionalized implants were stable and functional, without pain or other signs of inflammation. There was no peri-implant radiolucency or marginal bone loss, as summarized in Table 1.

Implant Stability and Osseointegration Speed

The ISQ was between 48 and 75 (63.2 ± 11.8) at the time of implant placement and between 68 and 81 (76.2 ± 5.2) at the commencement of loading (Table 1, Fig 6). The ISQ was greater than 65 at the time of loading for all implants tested. Five of the six implants tested showed an increase in ISQ during healing. In particular, the implants with initial ISQs below 70 showed impressive increases at the time of loading, ranging from 5 to 31. The osseointegration speed ranged from –1.11 to 8.16.

Marginal Bone Change

The marginal bone change measured at the mesial and distal aspects of each implant is listed in Table 1 and plotted in Fig 7. The MBL, which was an average of –0.35 ± 0.71 mm at the time of crown placement, had significantly increased to 0.16 ± 0.53 mm after 1 year, indicating an overall coronal gain in marginal bone contact, which in some cases even exceeded the level of the implant platform ($P < .05$). Marginal bone gain was seen at 11 of the 14 aspects measured, and no implants had marginal bone loss at 1 year of follow-up (Fig 7). In particular, all MBLs that were apical to the platform at crown placement increased, whereas those MBLs that were coronal to the platform maintained the same level (Fig 7). The average MBL change was 0.51 ± 0.35 mm after 1 year, which resulted in platform-level or supra–platform-level marginal bone in the majority of areas (9 of 14).

Complications

The 15-minute photofunctionalization process was initiated several minutes before anesthetizing the patient. By the time drilling was complete, the photofunctionalized implants were ready for placement, which resulted in no delays in surgery. Because of the superhydrophilic nature of the photofunctionalized

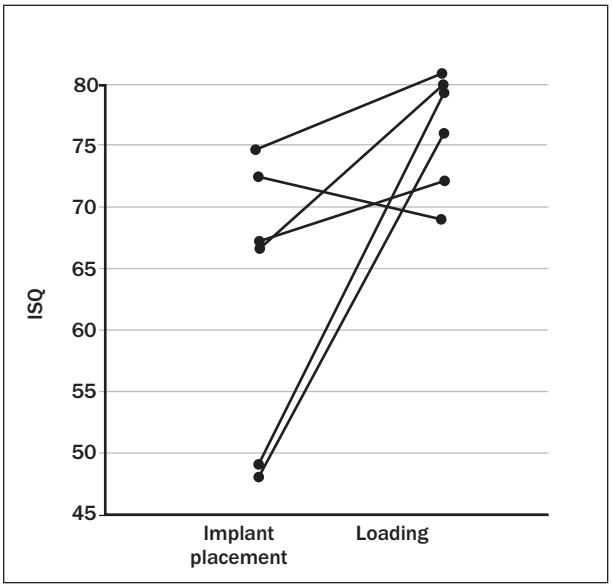


Fig 6 Changes in implant stability for photofunctionalized implants. ISQ values were measured at the time of implant placement and at the start of functional loading.

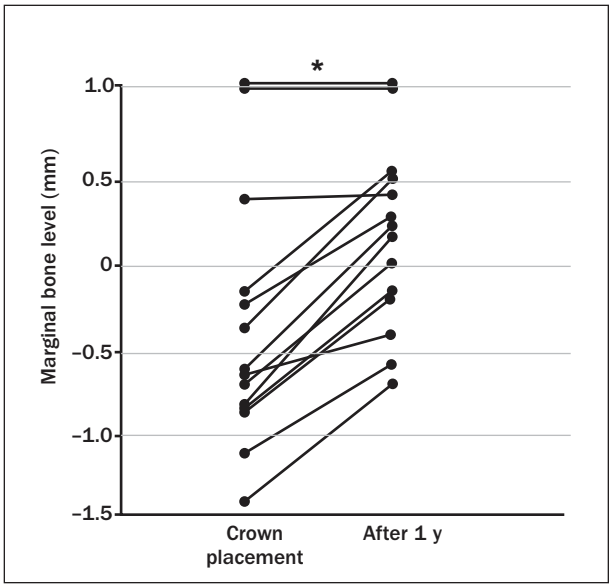


Fig 7 MBL changes around photofunctionalized implants. MBLs were measured at the time of definitive restoration and at 1 year. Negative numbers represent bone levels apical to the implant platform, and positive numbers represent bone levels coronal to the platform. Refer to Table 1 for mean values for MBLs and changes in MBLs. *$P < .05$.

implant surfaces, particular attention was given to ensuring that the implant did not contact saliva or surrounding soft tissue when being placed. No prosthetic or surgical complications or procedural difficulties were observed with regard to the use of photofunctionalization.

DISCUSSION

This is the first study to report on the clinical use of photofunctionalized dental implants. Despite the challenging bone conditions studied in this case series, all implants demonstrated successful osseointegration and functioned as expected, with excellent soft tissue health and esthetics that were maintained at 1 year of follow-up.

An animal study that examined the effect of deficient cortical bone support on osseointegration showed that implants placed without cortical bone support had a 60% reduction in the strength of osseointegration compared to those with cortical support.[29] Photofunctionalized implants improved this osseointegration to levels observed for implants with cortical support. The effect was explained by the enhanced capability of the photofunctionalized implants to induce osteogenesis, beginning at the implant interface and rapidly spreading to, and connecting with, the surrounding bone. In contrast, delayed osteogenesis begins at the surface of remote cortical bone and slowly approaches the implant interface with untreated implants. In other words, photofunctionalized implants are capable of inducing contact osteogenesis,[66] even under suboptimal conditions, while untreated implants rely on distant osteogenesis.[66] These findings suggest that photofunctionalized implants may overcome the compromised bone healing associated with a significant peri-implant gap; the case of implant placement into a fresh extraction socket (patient 3) may have represented this scenario. Implant placement into a fresh extraction socket is known to be associated with a higher failure rate than placement into healed sites, and failures usually occur during the early stage of healing.[7] According to the literature, implants placed into extraction sockets should be kept unloaded for 4 months[39] or 5 to 6 months[61]; it was therefore noteworthy that, in the present study, a degree of osseointegration sufficient for loading was achieved after only 2.1 months of healing after placement of a photofunctionalized implant. With respect to establishing and maintaining the strength of osseointegration, ISQs for implants in extraction sockets have been shown to remain unchanged or even decrease slightly after 6 to 12 months of healing.[42,61] The high ISQ of 72 at provisionalization obtained with photofunctionalization in this patient, in addition to the average ISQ increase of 2.4 per month, was exceptional and justified early loading (2.1 months after placement). Furthermore, it was impressive that the process of

osseointegration continued to mature and extend even after functional provisionalization, as vividly detected in radiographs (Fig 4g). This phenomenon appeared to embody the aforementioned contact osteogenesis in the local environment without cortical support.

Placement of an implant into the site of a currently failing, or previously failed, implant is considered one of the most challenging clinical scenarios.[67–69] Preexisting inflammation and a decreased potential for osteogenesis may compromise bone-implant integration, resulting in substantial decreases in success rates to levels as low as 70%.[67] Moreover, horizontal and vertical gaps are often present between the implant and the alveolar bone. In such cases, an extended healing time of 5 months or more may be required before placement of implants, along with additional healing of 9 months or more after placement.[69,70] In patient 1, despite the peri-implant gap of 3.5 mm, a photofunctionalized implant placed immediately after removal of the failing implant osseointegrated and was successfully loaded after 2.1 months, followed by an asymptomatic and complication-free outcome up to 1 year. Therefore, the clinical outcomes obtained in patients 1 and 3 appear to be consistent with the results of published animal studies.

The degree of reduction in the strength of osseointegration caused by the use of short implants has been assessed in an animal model.[17] Implants with 40% shorter length resulted in a decrease in implant anchorage of 50% or more. Shorter implants that were photofunctionalized had a strength of osseointegration that was double the usual strength, eliminating the disadvantage of short implants.[17] This was explained by the expansion of the load-bearing interface around photofunctionalized implants,[17] which benefitted from the significant increase in BIC.[24] While sinus grafting has been proven an effective measure to expand the indications for implants and improve implant stability, success rates after sinus augmentation are not as high as those seen for regular implant placement without such surgical intervention.[71] In patient 2, an implant was placed into a first molar site with simultaneous sinus elevation. The implant was supported only by native bone for the coronal 45% of its length, with the additional challenge of poor bone quality, as confirmed by an ISQ of < 50. Even under this condition, the ISQ increased from 49 to 80 after 3.8 months, yielding an ISQ increase of 8.16 per month. The rate of ISQ increase obtained here was much higher than that reported for maxillary implants in the literature (0.0 to 1.0).[58,59,61,72] With respect to the healing time required, implant placement combined with sinus elevation is often performed using a staged approach, with a total healing time of 8 to 14 months.[73] The use of a photofunctionalized implant and a simultaneous approach to grafting and implant placement resulted in successful loading after only 3.8 months in this case.

Implant osseointegration in augmented bone is considered to be difficult because of the limited availability of regenerative cells and decreases in other osteogenic metabolic activities.[74,75] This requires a longer healing time and results in more frequent soft tissue encapsulation and progressive peri-implant bone resorption.[76–78] Furthermore, the extent to which the native bone supports the implant is a crucial factor in determining implant prognosis.[5] When implants are placed in augmented bone, it is generally thought that a 6-month healing period is required to secure osseointegration prior to loading.[79] Implant placement in a site after multiple site development procedures, such as a combination of vertical ridge augmentation and sinus elevation, may require a healing time that is further extended, up to 13 months.[80] Here, photofunctionalized implants were placed into a site treated with combined vertical ridge augmentation and sinus elevation and were successfully loaded after 4.5 months (patient 4). This was in spite of a very low percentage of native bone support (between 25% and 30%).

Contrary to the current understanding that marginal bone loss is unavoidable within the first year of implant placement,[72,81–84] there was an overall gain in MBLs in this clinical series. The average gain after 1 year was approximately 0.5 mm, which resulted in an MBL above the implant platform. Notably, none of the sites showed marginal bone loss. One interesting finite element analysis–based study simulated the distribution of peri-implant stress when BIC was 98.2% and 53.0% in implants with and without photofunctionalization, respectively.[85] The concentration of stress around the implant neck was significantly reduced by the 98.2% BIC, as demonstrated by the fact that the stress around 7-mm-long implants with 98.2% BIC was even lower than the stress around 13-mm-long implants with 53% BIC. This study suggested that, although it is unclear what concentration of stress triggers bone resorption around the area, increased BIC effectively improved the distribution pattern of peri-implant stress and may be a potential strategy to preserve peri-implant marginal bone. The observation in this report warrants further longer-term studies to establish the effect of photofunctionalization on the anatomical stability and physiologic health of peri-implant bone and soft tissue.

Photofunctionalization-induced physicochemical changes include the removal of hydrocarbon, optimization of electrostatic charges on titanium surfaces, and regeneration of superhydrophilicity.[16,53,86–88] In vitro studies have demonstrated that hydrophilicity alone does not increase the amount of protein and number of osteogenic cells attached to titanium surfaces, and that unfavorable electrostatic charges on titanium surfaces

substantially reduce the recruitment of osteogenic cells to titanium surfaces, even when they are hydrophilic.[87,88] It is also known that the number of cells attached to titanium surfaces correlates with reductions of surface carbon, but not with the degree of hydrophilicity.[21,24,44] In the general field of biomaterials research, the role of surface hydrophilicity in determining bioactivity remains contentious.[89] It has not been universally demonstrated that a more hydrophilic surface makes for a more biocompatible material. For instance, a polymer surface with improved hydrophilicity reduces fibroblast proliferation,[90] while more hydrophobic polymer scaffold materials are effective in promoting bone regeneration.[91] There are commercially available hydrophilic dental implants that are stored in solution to preserve their hydrophilicity.[92,93] However, these surfaces need careful interpretation with respect to their clinical advantage,[89] since there is little information regarding their other physicochemical properties, including carbon percentage, electrostatic status, and time-related physicochemical changes. In fact, fewer cells attach to these hydrophilic surfaces than to hydrophobic surfaces with identical surface morphology.[94] This biologic property is completely different from that of photofunctionalized surfaces, which enhance the recruitment and attachment of cells considerably.[21,24] In addition, one definite difference between photofunctionalized implants and these commercial implants is that photofunctionalized implants are dry prior to use but highly wettable when they make contact with blood, whereas the commercial products are wet with solution before use. It should also be remembered that photofunctionalized surfaces are converted to chemically clean and genuine titanium surfaces.

Although various site development procedures enable or facilitate implant placement, they are also risk factors for implant failure and necessitate protracted healing. In this case series, all implants showed ISQs higher than 65 at loading and were safely loaded earlier than reported in the literature or earlier than suggested in common protocols. In the present series, the osseointegration that was established early was maintained during 1 year of follow-up. Although interpretation is necessarily limited by the number of patients reported here and the relatively short-term follow-up period, these successful outcomes suggest that photofunctionalized implants are useful and effective for challenging clinical cases and warrant further clinical study. Since photofunctionalization is effective on all examined surface topographies of titanium-based materials,[25–27,56] the technology seems versatile and applicable to a wide range of dental and orthopedic implants. Finally, no surgical or prosthetic complications were observed, suggesting that the technique is both practical and safe. If surface modification technologies are needed to expand the indications for implant therapy, shorten the healing time, and increase success rates, particularly in challenging clinical situations, photofunctionalization appears highly suited to achieving these goals.

CONCLUSIONS

Within the limits of interpretation of a small case series, the use of photofunctionalized dental implants in these clinically challenging cases appeared to result in osseointegration in a shorter period of time than currently suggested by standard protocols and the published literature. In addition, the increases in implant stability and osseointegration speed were considerably greater for photofunctionalized implants than similar results reported in the literature. During a 1-year follow-up period, the marginal bone level increased toward the coronal for all photofunctionalized implants whose platform had been subcrestal at crown placement, while those implants that had supracrestal peri-implant bone at crown placement maintained their marginal bone level without loss. No surgical or prosthetic complications were reported up to 1 year after loading. The procedure for photofunctionalization is simple and applicable to titanium-based and titanium alloy–based materials of various surface types. Together with other in vitro and in vivo data, the promising clinical outcomes presented in this preliminary study suggest that photofunctionalization is useful and effective for challenging clinical situations and represents a novel avenue to overcome some of the ongoing challenges in implant dentistry. Further mid- and long-term clinical studies are warranted.

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